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(54) Increasing petroleum recovery

(57) A process for increasing the recovery of petroleum from a subterranean formation penetrated by a wellbore comprises the simultaneous stimulation of the producing formation from the wellbore by means of elastic waves, created by a vibrator installed in the wellbore so that the elastic waves which are superimposed reduce the adherence forces in the layer between oil/water and the rock formation, and the oscillating electrical stimulation of the same layer. The electricity heats the formation by means of resistive heating, and increases the pressure, thereby eliminating the surface tensions between the faces of the fluid as a consequence of the oscillatory actions of the ions in the surfaces of the fluid; in addition, it reduces the viscosity of the fluids. The process is achieved as the flow of petroleum produced in wells, thus treated, acts as a cooling agent which removes the heat released by the well area and thus allows a larger input of energy than in any other method known so far. The electrical energy is passed down the borehole to supply a well casing penetrating the formation and the vibrator.

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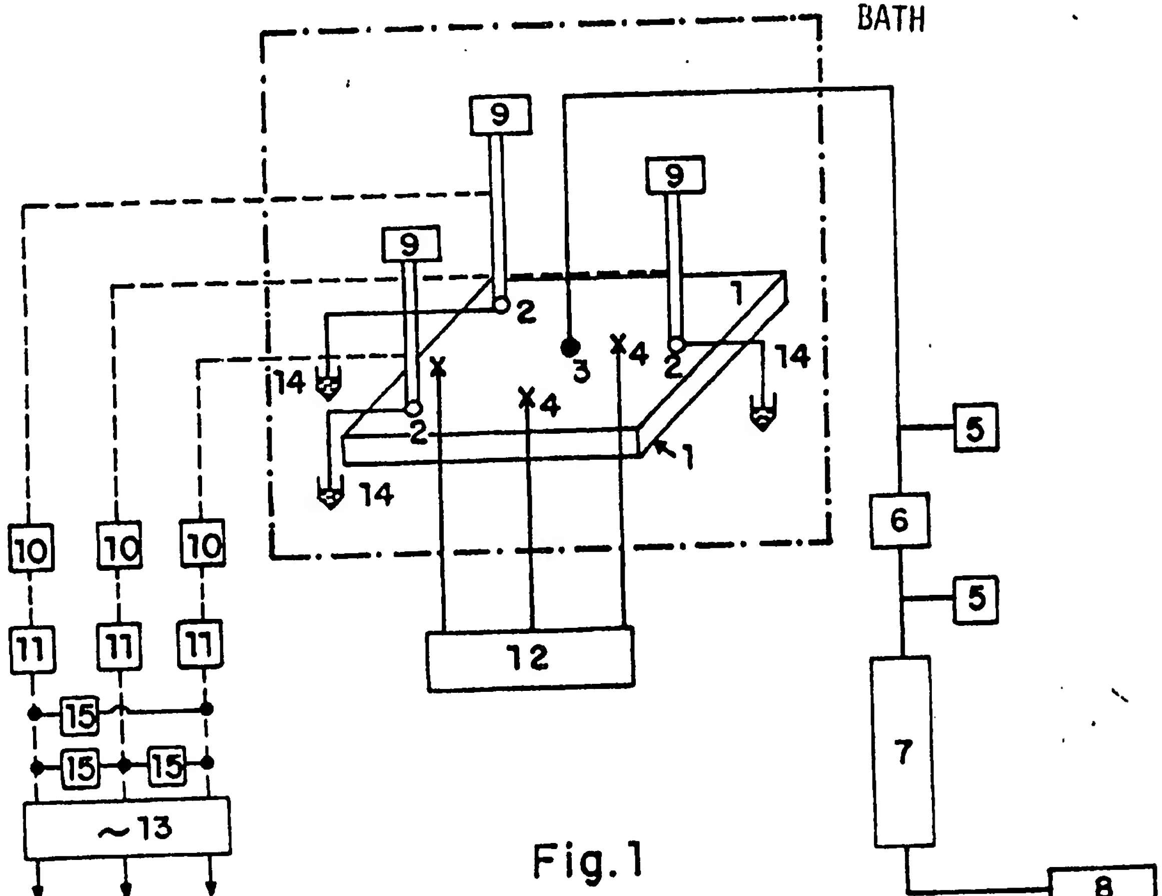

Fig.1

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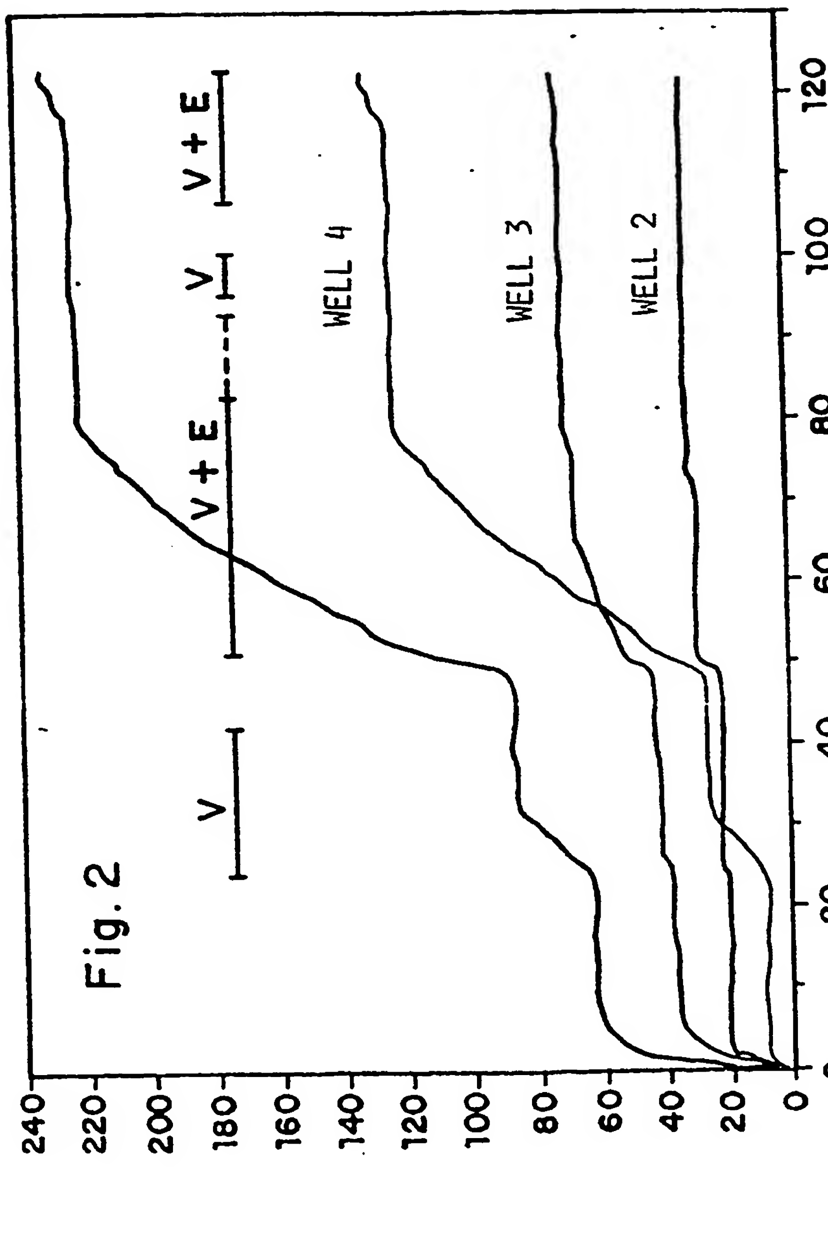

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Fig. 2

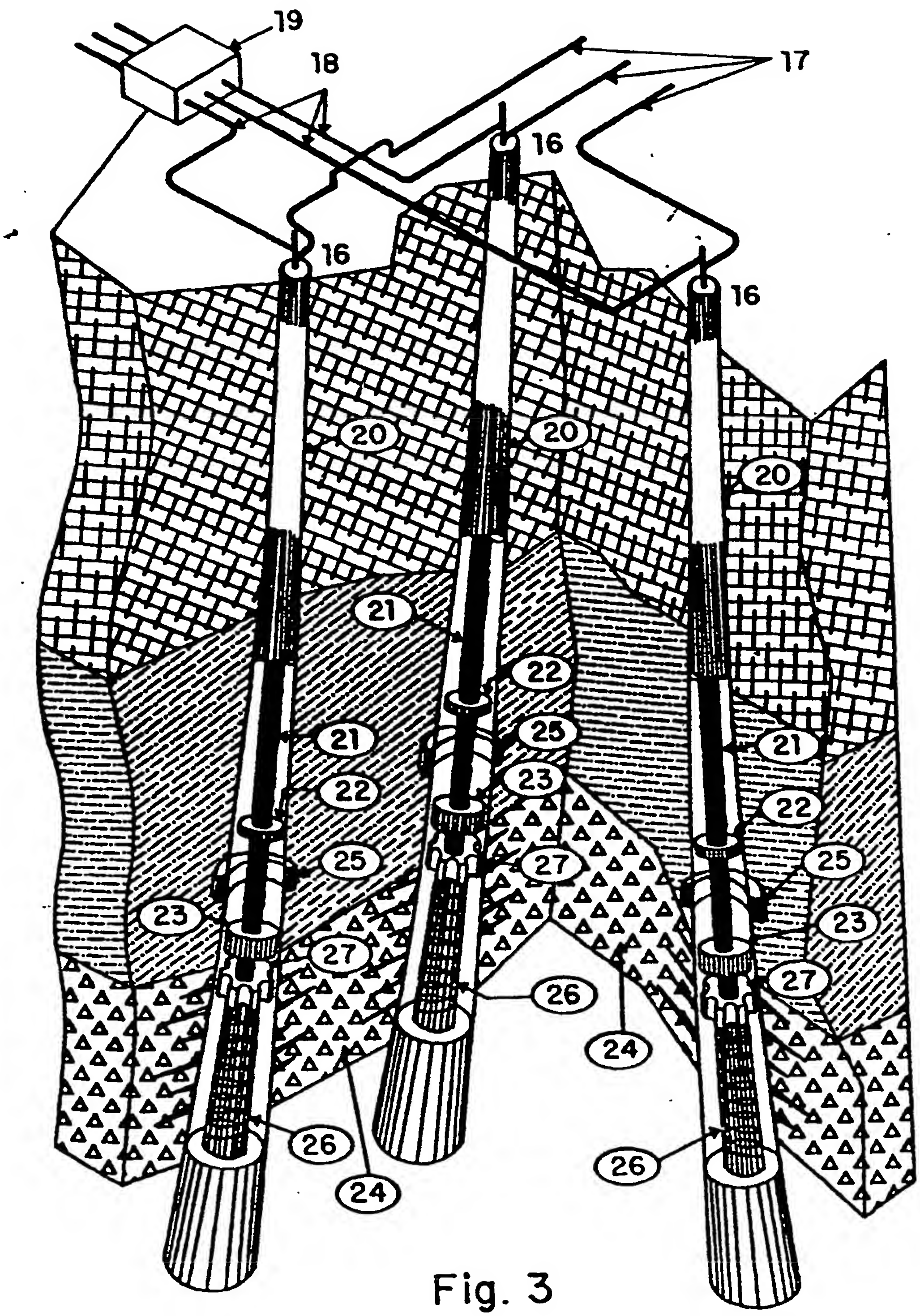
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Fig. 3

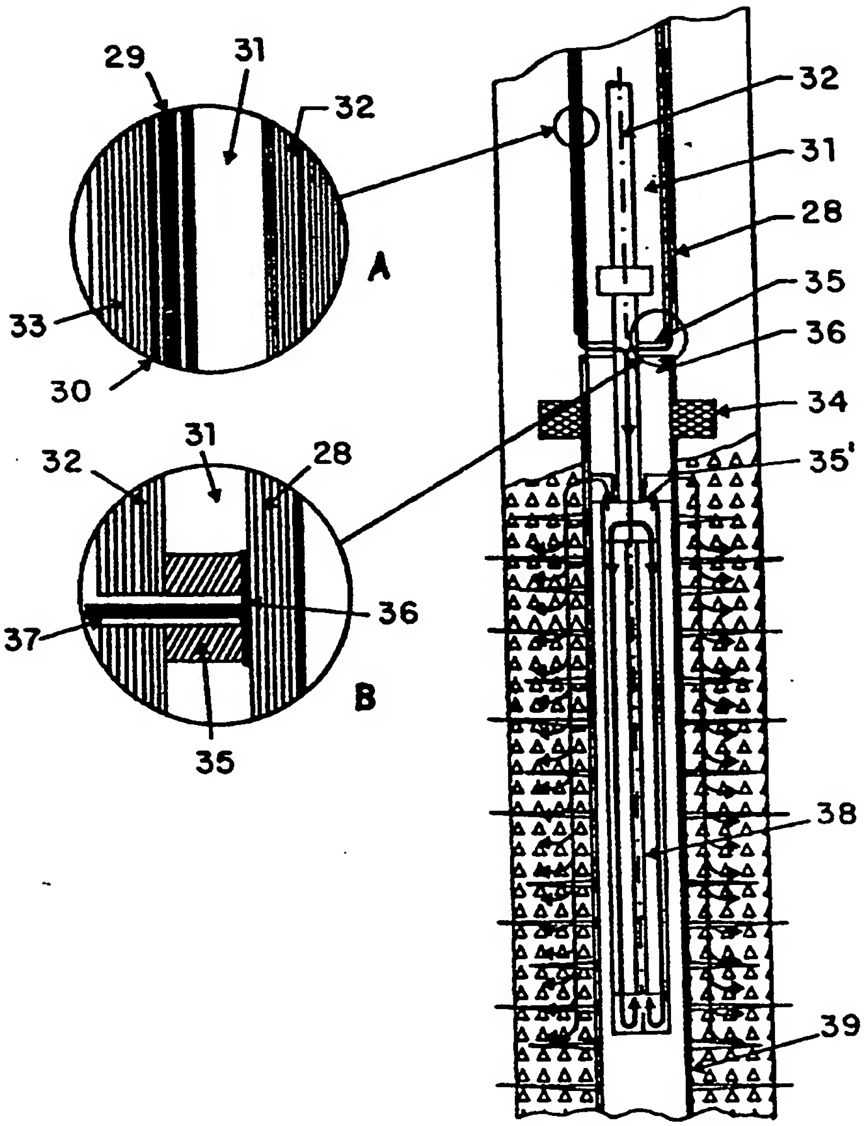
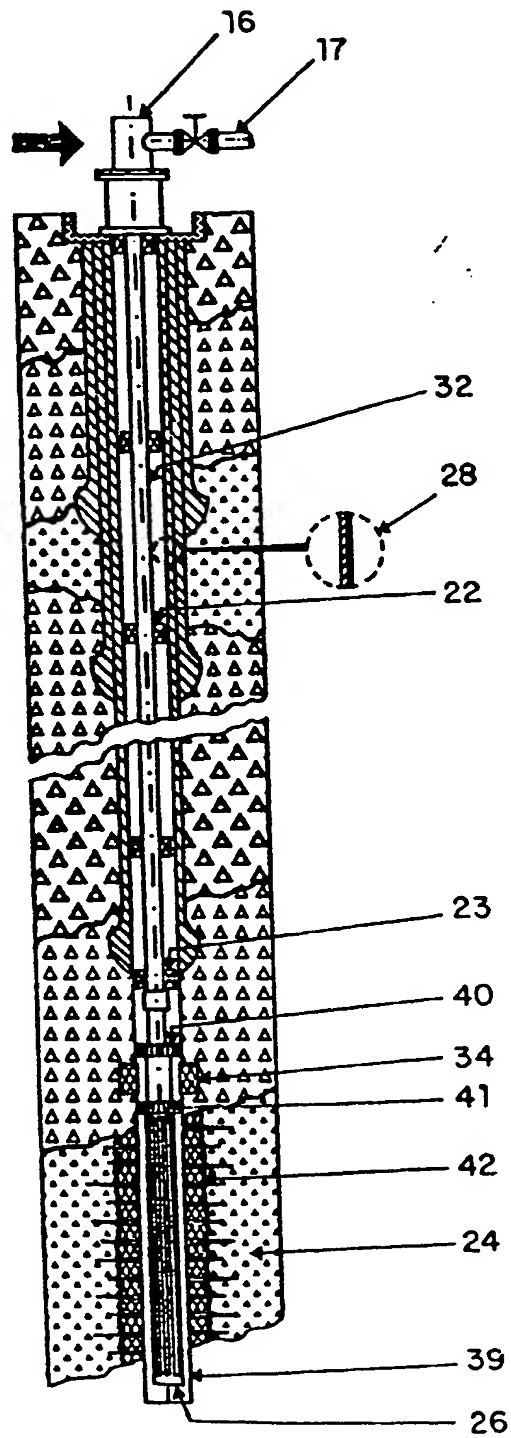


Fig. 4



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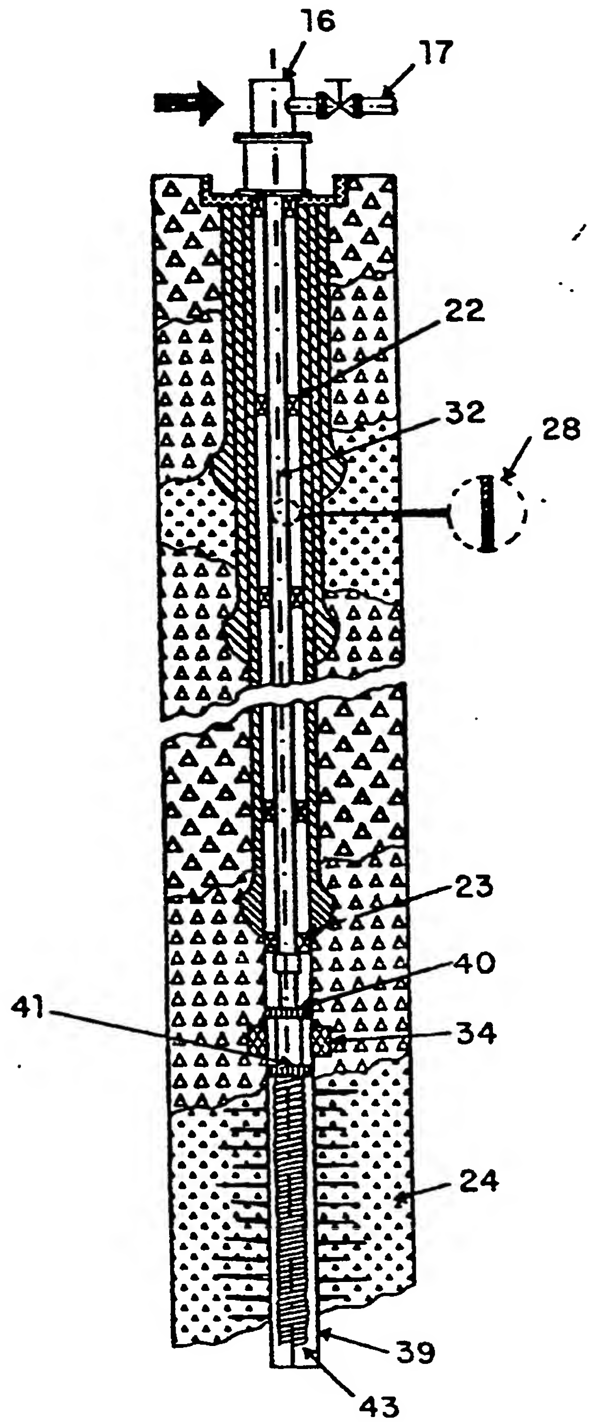

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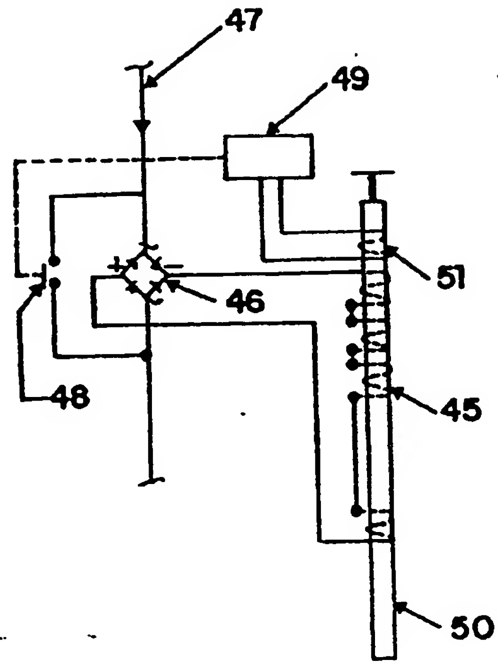

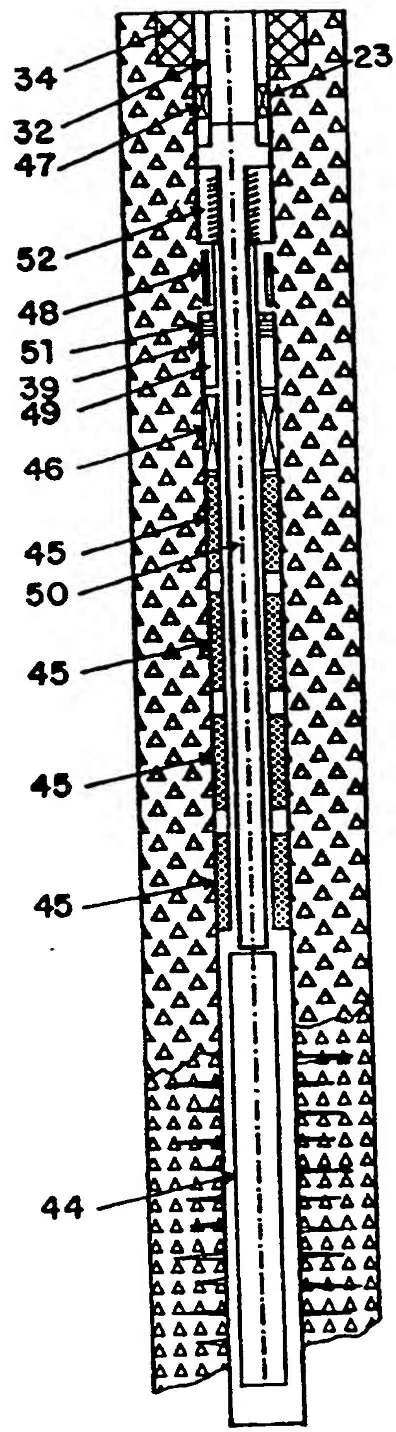

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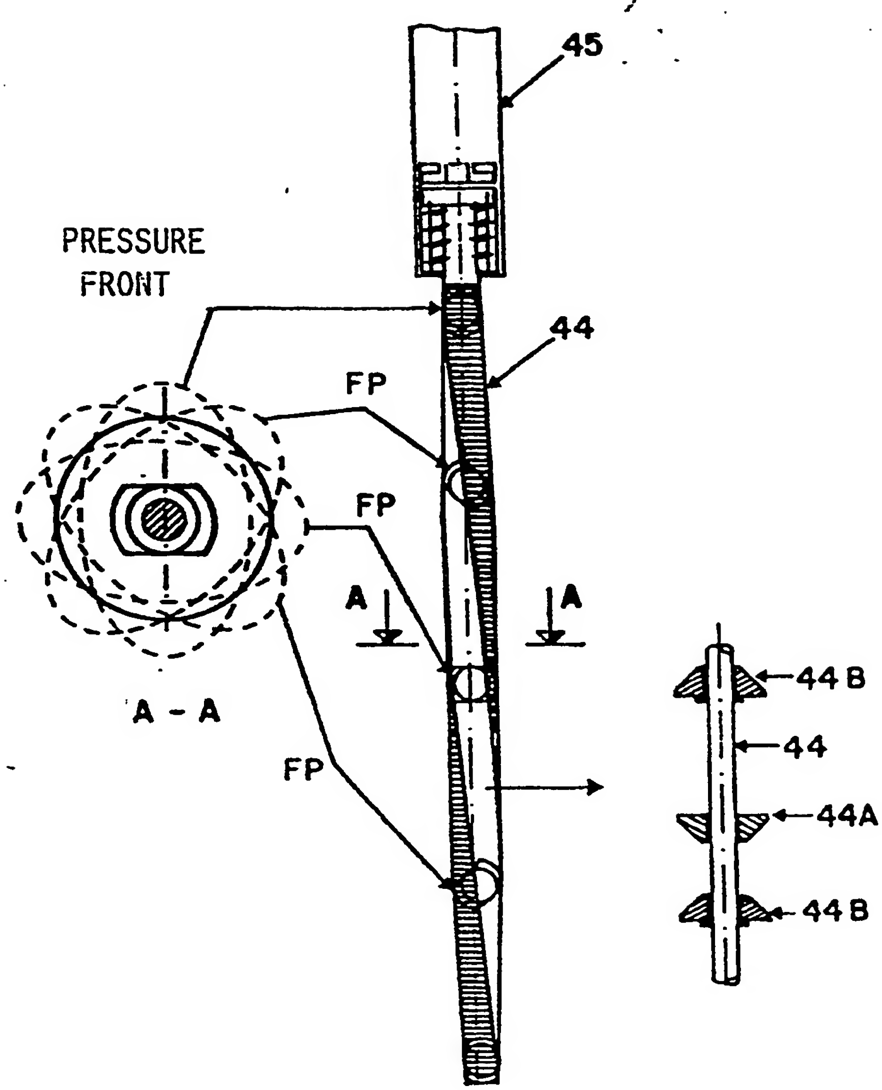


Fig. 8

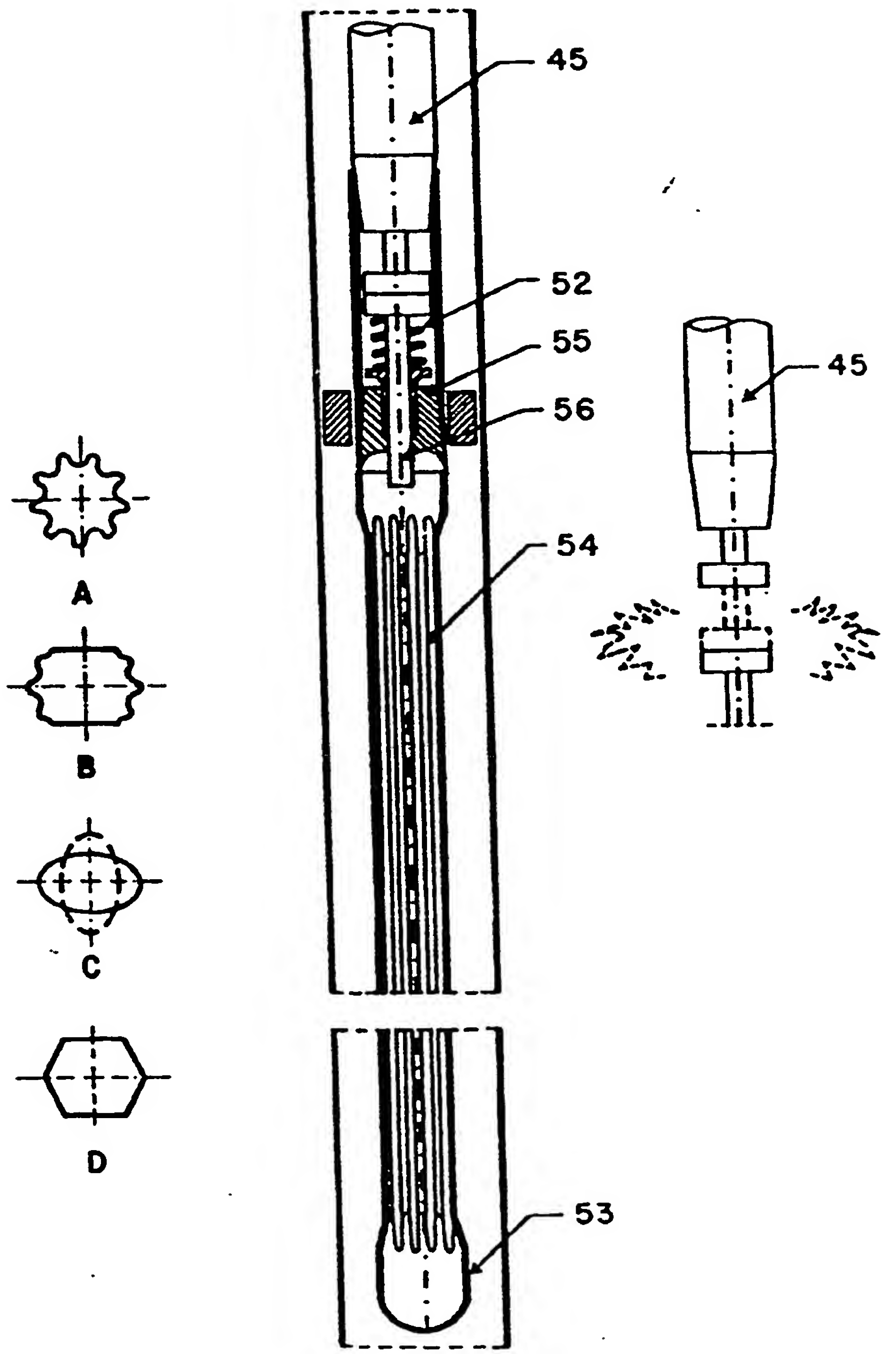
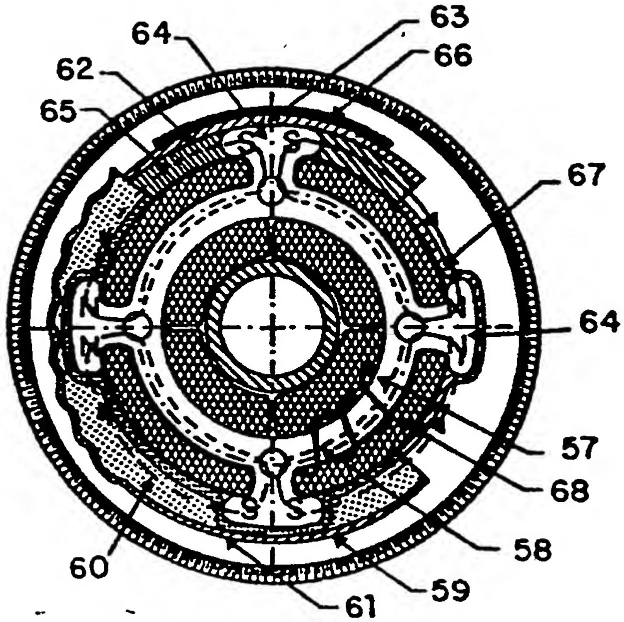
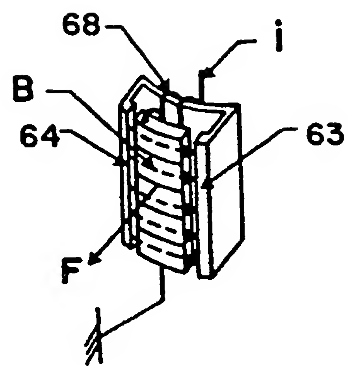


Fig. 9





DETAIL A

Fig. 10

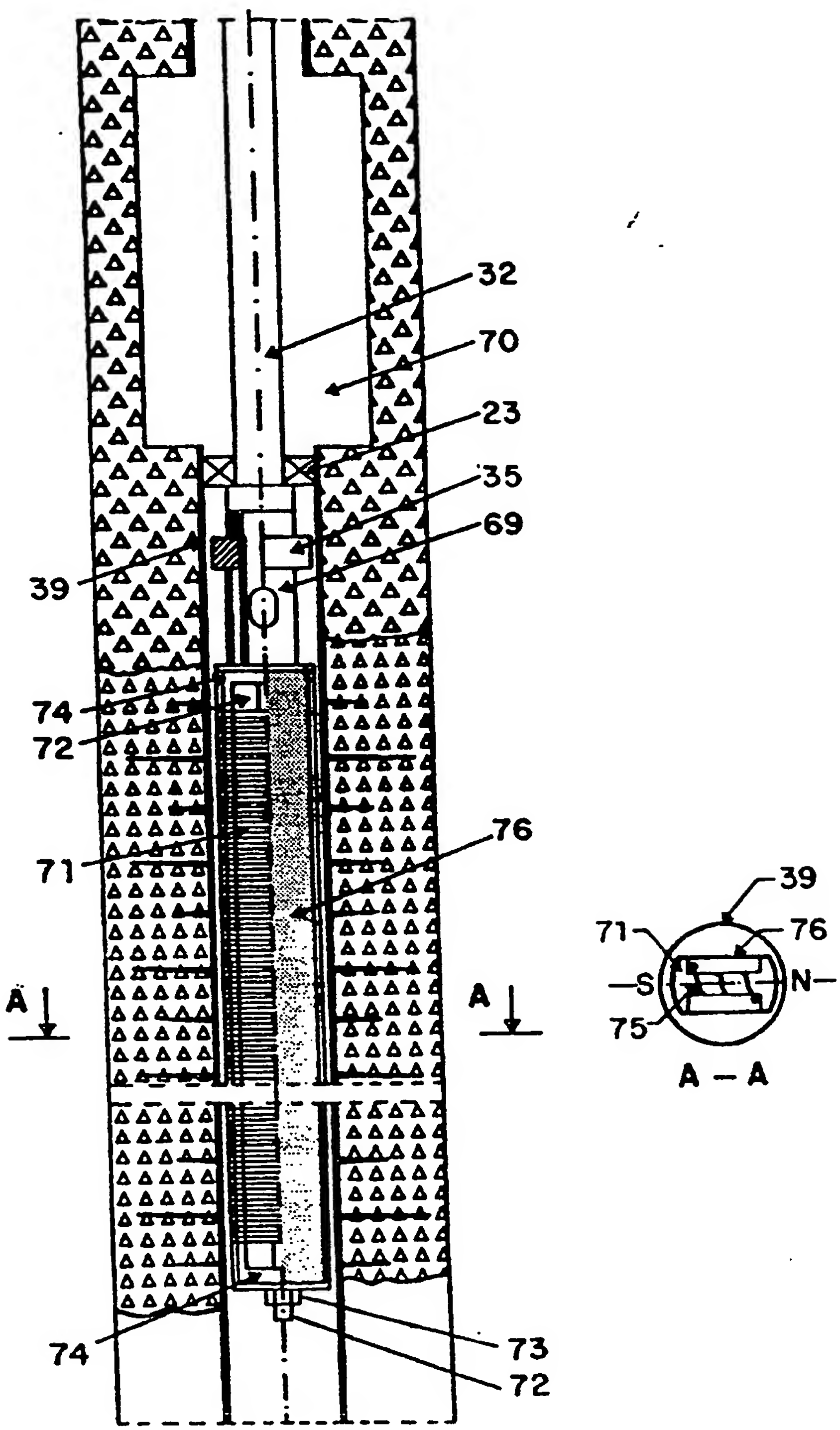


Fig. 11

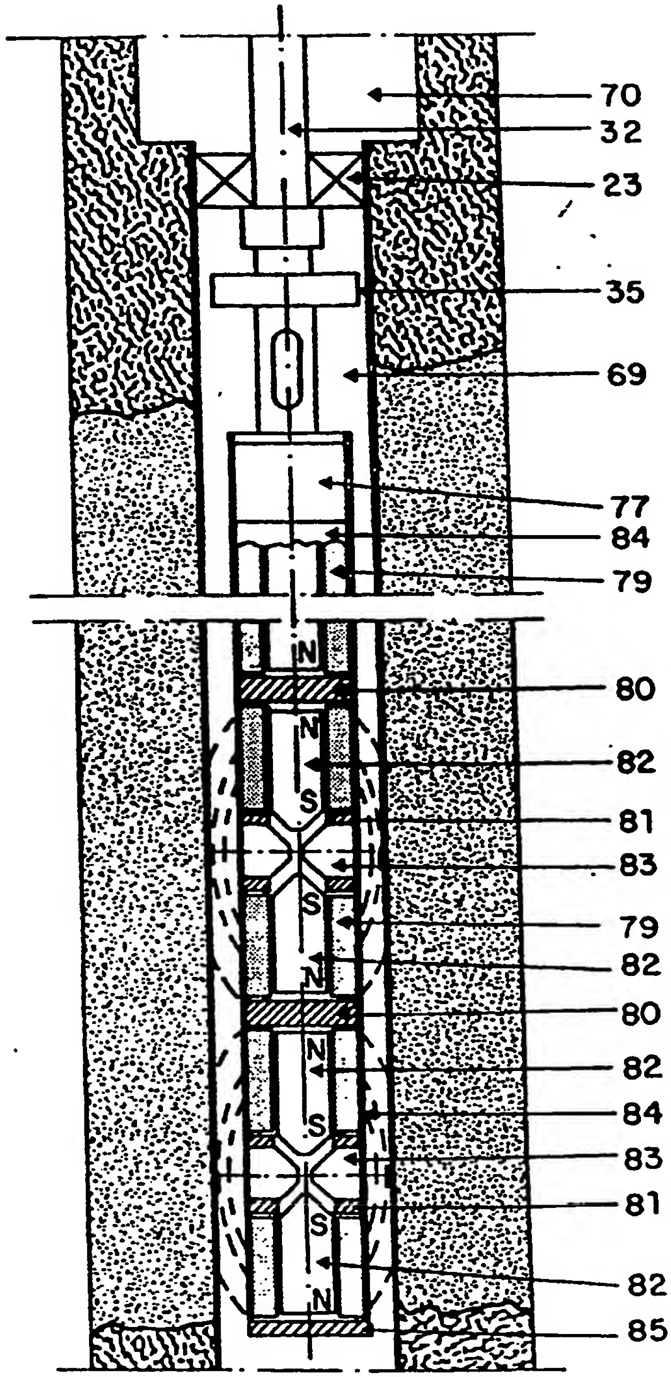

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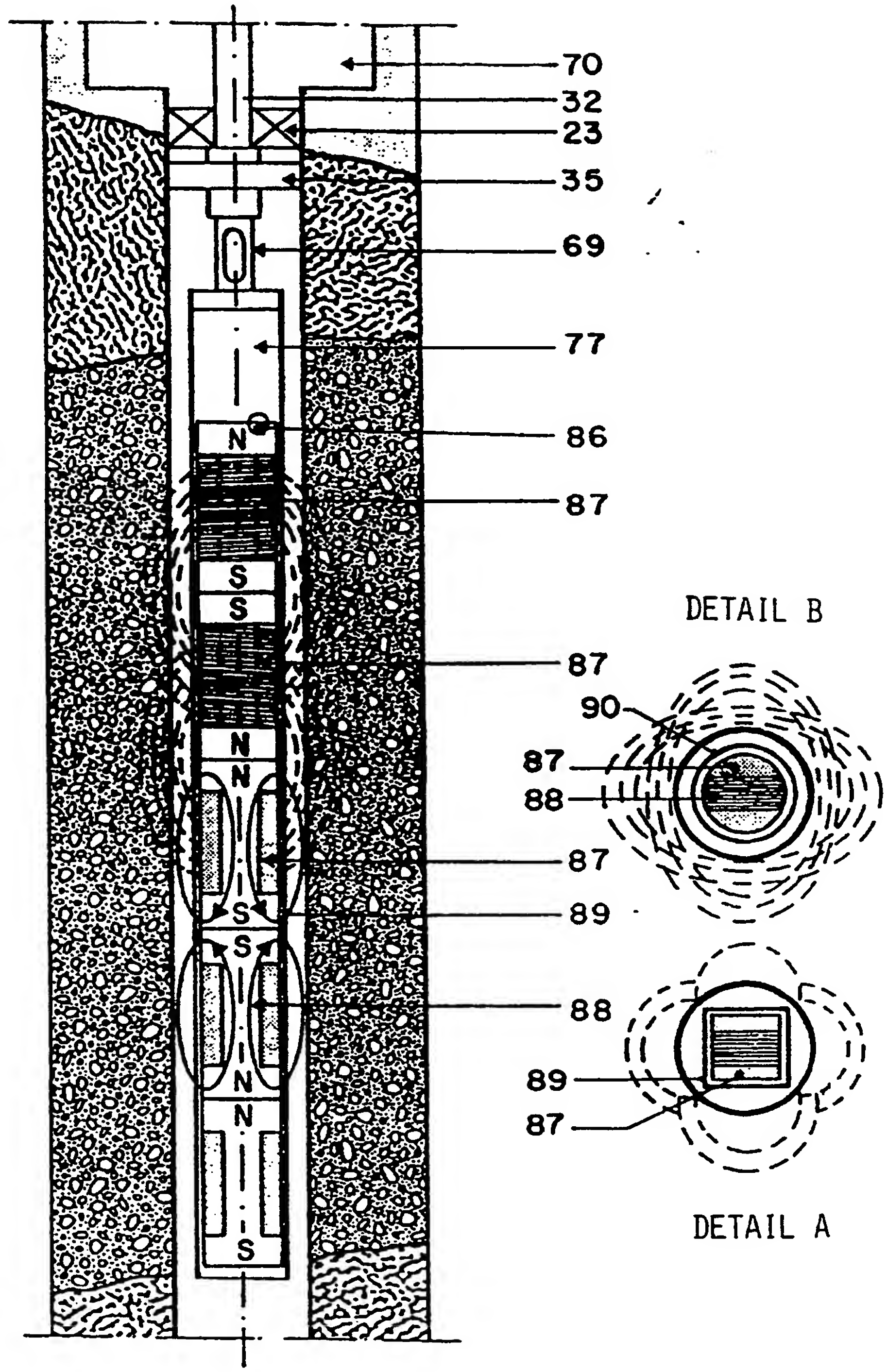
Fig. 12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DETAIL A

Fig. 13

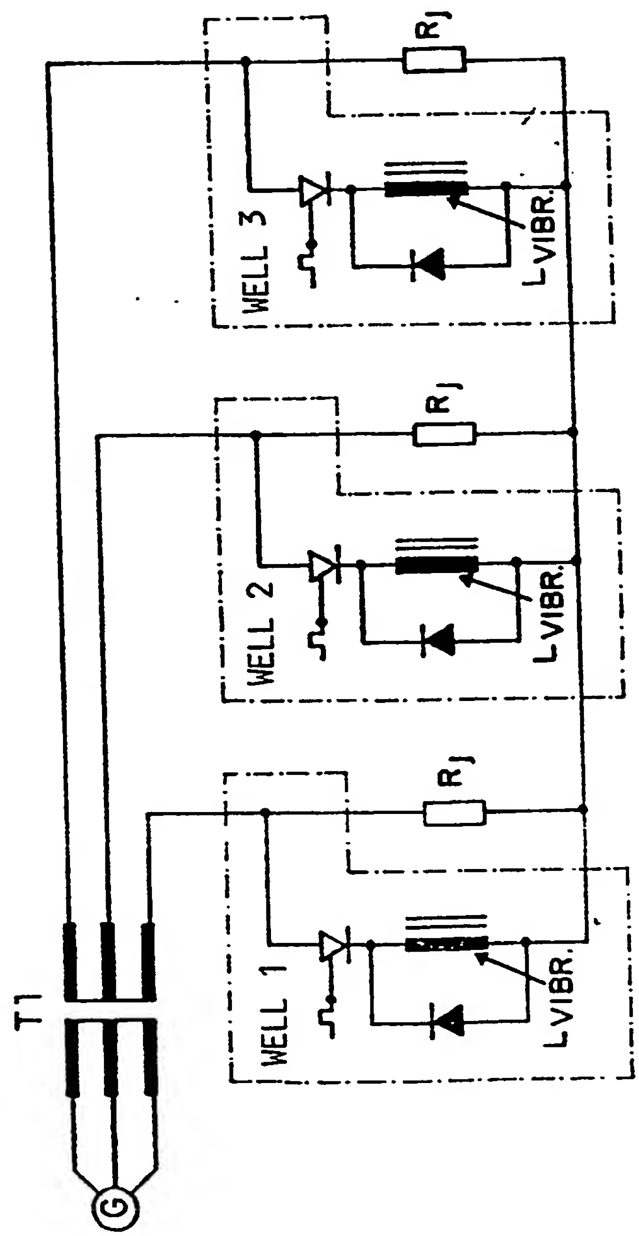

Fig.14

"PROCESS AND APPARATUS FOR INCREASING PETROLEUM RECOVERY FROM PETROLEUM RESERVOIRS"

This invention refers to an improved method for petroleum recovery, by means of electrical and acoustic stimulation of formation layers, as from the same petroleum wells through which petroleum production is developed.

Hydrocarbons known as crude oil are found in the world usually retained in sandstones of different porosities. The reservoirs lay from a few meters to several thousand meters below the earth surface and the seabottom, and vary largely in size and complexity, with respect to their fluid and gas contents, pressures and temperatures.

Petroleum is produced by means of wells drilled into the formations. The well itself is a complicated construction, including casings which protect the well bore against the formation itself and the pressures exerted by the reservoir fluids. Depending upon the depth, the casings are subject to a stepwise reduction in diameter. In other words, pipe diameter decreases as depth increases. It is not unusual to have 50" (127cm) casings in the upper regions and 7.5" (19.05cm) casings in the lower ones.

Petroleum itself is drained from the productive formation by means of holes drilled in the casing, being, thereafter, lifted to the surface through what is referred to as production tubing. This tubing is centralized inside the casing by means of special centralizers, so that an annular gap exists between the production tubing and the casing.

Petroleum is initially produced due to the original reservoir pressure being higher than the complex forces of fluid adherence to the porous media. As pressure decreases in the course of production, a point of equilibrium is reached in which the adhesion forces are higher than the remaining pressure. At this point most of the petroleum is still in the reservoir. It is estimated,

as a global average, to be equal to nearly 85% of the petroleum which was there initially, but the recovery indexes vary largely from one reservoir to another. As an example we mention the Ekofisk field, in the North Sea, where the primary recovery index was 17% of the original oil in place (OOIP), and the Statfjord, where said index is estimated in 45% of OOIP.

The object of all methods designed to improve petroleum recovery is, therefore, that of trying to overcome those adherences. The theoretical base to explain the cause of those adherences is as follows:

A - forces due to wettability

B - forces due to permeability

C - capillary forces

D - adhesive and cohesive forces

It is convenient that the adherence forces dealt with in this invention be explained more in detail.

A - WETTABILITY

Wettability is one of the main parameters which affect the location, the flow and the distribution of reservoir fluids. The wettability of a reservoir affects its capillary pressure, its relative permeability, its behaviour under water injection, its dispersion, and its electrical properties.

In an oil/water/rock system, wettability is a measure of the affinity which the rock exhibits to oil or to water. The wettability of reservoir rocks varies from strongly waterwet to strongly oilwet. In case the rock does not exhibit any strong affinity for either fluid its wettability is said to be neutral or intermediate. Some reservoirs exhibit a wettability which is heterogeneous or localized, as a result of crude oil components which are strongly absorbed in certain areas. Thus, part of the rock becomes strongly oilwet, whereas the remainder may be strongly waterwet. In other reservoirs what is referred to

as mixed wettability may be found, since oil remains localized in the largest (oilwet) pores, in the form of continuous paths which pass by the rock, whereas water remains restricted to the smallest (waterwet) pores.

Three methods are presently utilized to quantitively measure the wettability: contact angle, Amott method and USBM method. Through the contact angle one measures the wettability of crude oil with brine in a polished mineral surface. The method serves to verify the effect on wettability of factors such as temperature, pressure and chemical action.

It is believed that most minerals present in petroleum reservoirs, particularly silicates, are originally waterwet. The arenitic reservoirs were deposited in aqueous environments to which oil migrated later. In the course of that process the wettability of reservoir minerals may be altered by the adsorption of polar compounds and/or deposits of organic matter originally present in crude petroleum. The polar extremities of those molecules may be adsorbed onto the rock surface, forming a thin organic film, which in its turn renders the surface oilwet. Depending upon the temperature and pressure in the reservoir, those mechanisms may alter the degree of wettability. Little research has been conducted to investigate how a mechanical interference can affect the wettability. The wettability of an oil/water/rock system depends upon the adsorption and desorption of polar compounds (electrical dipoles) in crude petroleum on the mineral surface, which in its turn depends upon the type of solubility of those compounds in the reservoir fluid.

To approach the problem of wettability one must associate these electrical dipoles with the mechanical stimulation so that the wettability is not allowed to return to its original state.

B - PERMEABILITY

Permeability is the capacity of the porous rock to conduct fluids, that is, the property which characterizes the facility with which a fluid can flow through a porous medium when subject to the influence of the application of a pressure gradient. Permeability is defined by Darcy's law, as a macroscopic property of the porous medium. Permeability is evidently related to the geometry of the porous structure, its porosity, tortuosity, and distribution of pore size.

The concept of relative permeability is used in the situations in which two immiscible fluids, such as oil and water, flow simultaneously through a porous medium. Their permeabilities are independent of the flow rate and of the fluid properties, and depend exclusively on the fluid saturations within the porous medium. The measurement of relative permeability is a critical factor in reservoir engineering, since it constitutes the predominant factor for the knowledge of flow properties in a petroleum reservoir.

Controlling or improving the permeability is, then, a most important factor in improving the sweeping efficiency in displacements with water. It must be said that the displacement with polymers is the method most utilized in mobility control. Water-soluble polymers are added to the water to be injected with the purpose of improving the mobility ratio, through the increase in viscosity and reduction of the permeability of the zones invaded, and, thus, prevent the water from breaking through prematurely.

A great deal of research has been conducted for the purpose of creating polymers sufficiently inexpensive for this object, but with little success so far.

C - CAPILLARY FORCES

The equilibrium saturation in a petroleum

reservoir prior to initiating its production is controlled by rock geometry and by fluid characteristics. Since water and hydrocarbons are immiscible fluids, a pressure differential - the capillary pressure - exists between the two fluid phases. If a wet fluid is displacing a non-wet fluid, the critical capillary pressure - depending upon pore size - must be overcome by the pressure differential in order to displace the wet fluid phase from those pores.

The ratio between (i) the pressure differential applied (equivalent to the capillary pressure) and (ii) saturation characterizes the distribution of pore dimensions. The curve of critical capillary pressure verified for reservoir rocks serves to indicate the oil distribution in the reservoir and is, therefore, a major parameter in the prediction of the oil saturation at different depths.

The capillary pressure is usually measured by the centrifugal method, through which a rock sample with original reservoir fluid saturations is immersed in the wetting fluid and centrifuged at a series of selected angular velocities. For each velocity the average sample saturation is determined, and this, in its turn, is then correlated to the corresponding capillary pressure, by means of rather laborious numerical calculations (Hassler-Brunner method).

Since the capillary pressure may oppose oil recovery, particularly in the case of small pores, it is most important to be able to control or reduce the capillary critical point in the tertiary oil recovery.

Chemical methods are usually employed, based on tensoactives, such as surfactants to reduce the interfacial tension. However, the results described in the literature show that the utilization of tensoactives has produced limited results due to the high cost of those products and their large consumption by the reservoir rock.

D - ADHESIVE AND COHESIVE FORCES

The molecular forces which exist between two layers of different or similar substances are those which generate the adhesive or cohesive forces, respectively.

In the case of a fluid in porous rocks, adhesive forces exist between the fluid and the pore walls. Such forces appear particularly in the oil phase, as a consequence of the polar components in the hydrocarbons.

The adhesive forces are probably weaker than the capillary forces mentioned above.

Since petroleum plays a preponderant role in the world economy, considerable efforts are being made to extend the production, in addition to the so-called primary recovery or natural reservoir depletion. Various methods are known, discussed in the literature on the subject, as well as in ancient and recent patent documents.

The oldest technique, and for such reason the most well-known, has been that of injecting water or gas in what is usually referred to as injection well, aiming at increasing the pressure and thus "squeezing" some more petroleum from the well. Other well-known techniques consist of different chemical and thermal methods, amongst which we mention the following examples extracted from the book, "Enhanced Oil Recovery, 1, Fundamentals and Analyses", by E.C.Donaldson, G.V.Chillingarian, and F.Yen, ELSEVIER 1985.

<u>Chemical Injection</u> (alkalis) - This method requires a pre-washing to prepare the reservoir, and the injection of an alkaline solution or an alkaline polymer solution, which generates surfactants <u>in situ</u>, to release the oil. Thereafter, a polymer solution to control the mobility, and a driving fluid (water), is applied, to displace the chemicals and the oil bank resulting from the process of recovery towards the production wells.

<u>Carbon Dioxide Injection</u> - This method is a miscible-displacement process which is adequate for many

reservoirs. The most feasible method is usually the utilization of a CO_2 bank, followed by alternating injections of water and CO_2 (WAG).

Steam Injection - The heat, from the steam injected in a heavy-oil reservoir, renders this oil less viscous, thus displacing oil more easily through the formation, towards the production wells.

Cyclic Steam Stimulation - In this process, which usually precedes the continuous steam injection, injection occurs in the producing wells at time intervals followed by well shutting-in, for heat dissipation and later return to production. These cycles are repeated until the production index becomes smaller than a minimum profitable level.

In-Situ Combustion - This process encompasses the ignition and controlled burning in situ of the formation oil, using the injection of pure oxygen or air as comburant. The heat released and the high-pressure gases make it easy to displace the heavy oils towards the producing wells.

The textbook "Thermal Recovery", by Michael Prats, Monograph Volume 7, Henry L. Doherty Series 1986, deals with the technology involved in thermal recovery, the purpose of which is to heat the reservoir by different methods. The book mentions also other applications of reservoir heating, and teaches how to utilize the formation heating around the well area, by means of electricity. Electrical current is conducted by means of an isolated conduit, to a stainless steel screen at the bottom of the well area. The current then flows out of the screen, passes by the oil at the bottom of the well, through the casing, and returns to a grounded conduit at the surface. In addition to problems of electrical connections at the bottom of the well, when the current flows through the liquid, most of the energy is lost in the earth layers, even if its resistivity is lower than that of the

reservoir. This occurs because the current has to follow a distance hundreds of times longer in the earth layer.

Since those systems manage to deal with only part of the adhesion forces, large efforts have been made to overcome the problem, thus improving the recovery by means of more elaborated methods.

For the present application and for the patents to which reference is made as follows, it is important to present a more detailed description of the adhesion forces.

Description of the Prior Art

In the patents presented as follows there have been attempts to solve the above mentioned problem. Same are relevant to the present invention, since they can be seen as synthesis of the prior techniques.

US 2,670,801 (J.E. SHERBORNE) deals with the use of sonic or supersonic waves to increase the recovery and production of crude oil in petroleum formations. More precisely, it deals with the utilization of sonic and ultrasonic vibrations, together with secondary recovery processes which utilize driving fluids, such as water injection, or gas injection, or similar, to improve the efficiency of the driving fluid utilized for the extraction of the petroleum remaining at the formation.

US 2,799,641 (THOMAS GORDON BELL) refers to promoting the oil flow from a well by electrolytical means. It describes a method to stimulate the well area with electricity only, but utilizing direct current, since the purpose of the invention is to increase the recovery through the well-known phenomenon of electroosmosis.

US 3,141,099 (C.W. BRANDON) presents a device installed at the well bottom and is used to heat part of the well area by means of dielectric or arc heating. The only heating which may be achieved with this invention is resistance heating. It is not possible to heat by means of arc since this would require electrodes arranged rather

close between each other, and then the arcs would melt the rocks alongside them. As shall be seen later on, our invention is much different, since it utilizes a method to heat the reservoir, in situ, both electrically and with vibrations.

US 3,169,577 (ERICH SARAPUU) refers to the means to connect subsoil electrodes, between each other, by means of electrical impulses, and relates precisely to methods oriented towards inducing flow in producing wells. The purpose is to drill additional wells, as well as to create fissures or fractures near the well bore to increase, thus, the drainage surface of the wells and heat the hydrocarbons close to the well with the purpose of reducing the viscosity of such hydrocarbons.

US 3,378,075 (BODINE) refers to a sonic vibrator to be installed inside the well to subject it to high-level sonic energy only, so as to achieve sonic pumping in the well area. As a consequence of said high-level sonic energy (and without the utilization of such device associated to electrical stimulation), the effect of muffling generated in the reservoir drastically reduces the penetration of sonic energy. However, the method shows improvement effects in the well area and contributes to reducing hydraulic friction in the fluid flow. A similar method is used in the former Soviet Union, aiming at cleaning the pores in the well area, with good results.

US 3,507,330 (WILLIAM G. GILL) refers to a method to stimulate the well area with electricity alone in which electricity is passed "upwards and downwards" in the wells themselves, by means of separate conduits.

US 3,754,598 (CARL C. HOLLOWAY, JR.) discloses a method which includes the utilization of at least one injection well, and another production well, to cause the flow through the formation of a liquid to which oscillatory pressure waves are superimposed from the injection side.

US 3,874,450 (KERN) refers to a method of

arranging electrodes, by means of an electrolyte, aiming at dispersing the electrical currents in a subsoil formation.

US 3,920,072 (KERN) presents a method of heating a petroleum formation by means of an electrical current, and the equipment utilized for such purpose.

US 3,952,800 (BODINE) presents a sonic treatment for the surface of the petroleum well. The method, which is barely practical, intends to treat the well area by means of gas injection at the production well itself, and to subject the gas to ultrasonic vibrations to heat the petroleum formations.

US 4,049,053 (SIDNEY T. FISHER ET AL) discloses different low-frequency vibrators for well installation, and which are hydraulically driven by surface equipment.

US 4,084,638 (CUTHBERT R. WHITING) deals with stimulation of a petroleum formation by means of high-voltage pulse currents, in two wells, one an injection well and another a production well. It explains also how to obtain such electrical pulsations.

US 4,345,650 (RICHARD H. WESLEY) presents a device for electrohydraulic recovery of crude petroleum by means of an explosive and sharp spark generated close to a subsoil petroleum formation.

Although the creation of hydraulic shocks by means of a loaded capacitor is well known in the art, that invention presents an elegant vibrator as well as the advantages of utilizing shock waves to improve the recovery of petroleum.

US 4,437,518 (WILLIAMS) teaches how to use and build a piezoelectric vibrator in a well, for petroleum recovery.

US 4,466,484 (KERMABON) presents a method to stimulate the well area by means of electricity alone, but by means of direct current, since the purpose of the invention is to enhance the effect of electricity to recover petroleum through the well-known phenomenon of

electroosmosis.

US 4,471,838 (BODINE) describes another method to stimulate a well, with vibrations, which differs from the methods previously mentioned. Here are applied also the teachings of patent US 4,437,518 (WILLIAMS). The major difference in this case is that the energy is generated by a source installed at the surface. Considering the large depth of wells in general, this method is barely feasible.

US 4,558,737 (KUZNETSOV ET AL) discloses a bottom-hole thermoacoustic device, including a heater connected to a vibrating body. The intention is that the well area be heated and that the vibration of the heating device may activate the oil in that area, thus increasing the heat conductivity. It is a well-known phenomenon that any agitation increases the heat conductivity in a given medium.

US 4,884,634 (OLAV ELLINGSEN) teaches a process to increase recovery, by making the formations in the petroleum reservoir vibrate as close as possible to their natural frequency, so that the adhesive forces between the formations and petroleum can be reduced, and using electrical stimulation with electrodes installed in at least two adjacent wells. The process is achieved by filling a well with a metallic liquid to a height corresponding to the formation height, vibrating said metallic liquid by means of vibrator already installed, and at the same time effecting an electrical stimulation through the application of an electrical current to said electrodes.

USSR 832,072 (GADIEV AND SIMKIN) deals also with a vibrating heater installed inside a well, by means of which the vibrations are intended to increase the heat conductivity.

USSR 1127642 and 1039581 disclose various vibrators to be installed in a well to stimulate the well area alone.

CA 1096298 (MCFALL) discloses the construction of a resonator for fluids in which a fluid flow through and around a tubular or cylindric element, installed parallel to the fluid direction, generates in that flow vibrations or vibration waves. This is only one additional way to generate waves in a well without the combination and techniques for simultaneous use of electrical stimulation. The resonator design is analogous to a whistle in which the rupture of air and its change in direction generate sound waves.

The present invention relates to a process to recover petroleum from petroleum reservoirs, whether onshore or offshore, which includes the simultaneous stimulation of the formation by means of both vibrations and electricity. The process is achieved applying special vibrations inside the layers, so that said vibrations be as nearly as possible equal to the natural frequency of the matrix rock and/or of the fluids existing there.

The present invention also concerns the vibrators to achieve such process. Accordingly one aspect of the inventor provides a process for increasing the recovery of petroleum from petroleum reservoirs, wherein the producing formation is simultaneously subject to electrical and vibratory stimulation, in which the electrical current is supplied to the reservoir by means of an electric conductor installed in an annular gap between a production string and a well casing; wherein part of the energy is utilized to operate a vibrator attached to the end of the production string, the electrical connection being obtained by means of hydraulically driven connectors located at the vibrator and attached to the uncovered end of the electric cable; wherein said connectors conduct the electric current to the well casing which penetrates the producing formation at a point located above an isolation bridge; wherein part of the well casing is located above the producing formation and there is a cut at a certain

height above said producing formation defining a cavity which is filled with an electrically insulating material.

An advantage of the method of the present invention is that the process acts on the whole reservoir, thus making it possible to increase its recovery factor and to reestablish production in wells where production is paralysed.

Another advantage of the present invention is that production can occur while the wells are being stimulated.

Another aspect of the present invention provides apparatus for increasing the recovery of petroleum from petroleum reservoirs, comprising a mechanical vibrator energized by current impulses supplied to the petroleum reservoir itself from the main power source; wherein said vibrator receives energy causing a displacement which can be oriented approximately at 90° and/or amplify the course of the original displacement by hitting different kinds of expansion devices which may make the casing oscillate in different ways in accordance with the acoustic characteristics of the reservoir.

Brief Description of the Drawings

In order that the present invention may more readily be understood the following description is given, merely by way of example, with reference to the accompanying drawings in which:-

Figure 1 shows a laboratory installation in which feasibility tests were conducted.

Figure 2 presents the results of tests in laboratory scale conducted using the installation shown in Figure 1.

Figure 3 shows a schematic arrangement of three wells equipped with vibrators, to achieve the process of the invention.

Figure 4 constitutes a view in detail of the

bottom-hole electrical circuit.

Figure 5 presents a well ready for application of the process of the invention, equipped with hydraulically driven vibrators and connectors.

Figure 6 presents a well ready for application of the process of the invention, equipped with a vibrator which works vertically.

Figure 7 presents in detail a vibrator of the invention, which works also vertically.

Figure 8 shows another option for the arrangement of the vibrator hammer.

Figure 9 shows one additional option for the arrangement of the vibrator hammer.

Figure 10 presents details of another vibrator.

Figures 11, 12 and 13 present also other options for vibrators.

Figure 14 presents a schematic diagram for obtaining low-frequency sounds.

Description of the Invention

The basic principle of the present invention is in the elements and devices utilized to obtain the advantage of stimulating the formation by combining simultaneous vibration and electric current flow.

This is achieved by introducing special vibrations in the formation layers. Those vibrations should be as close as possible to the natural frequency of the matrix rock and/or that of the fluids.

The confirmation of the above mentioned principle was achieved by means of tests conducted in the laboratory, as shown in Figure 1, with the purpose of simulating on a laboratory scale the true conditions found in the formations. The tests were conducted as described below.

A sandstone block, with nearly 800mD of permeability and 22% of porosity, taken from an outcrop,

was isolated and saturated with water containing 40,000ppm of NaCl. Thereafter, the water was displaced with crude oil. The sandstone block was maintained at a temperature of about 38°C.

The porous medium 1 prepared as explained above was provided with three types of wells: namely production wells (2), an injection well (3), and observation wells (4) for temperature monitoring; and the laboratory rig was equipped with pressure sensors (5, 6), temperature probes (12) and equipment (10, 11, 13, 15) for electrical stimulation and sonic stimulation means (9), as well as gas feeding means (7) and liquid feeding means (8) to the system.

The tests were repeated several times utilizing different arrangements of vibrators and electrical power supply, and with (i) the effect of the stimulation utilizing vibration alone, (ii) electricity alone, and (iii) vibration and electricity simultaneously. The oil recovered was collected in flasks (14).

It was verified that the vibrations generate various effects in the fluids retained in the formations:

a) they release the cohesive and adhesive links, as well as a large part of the capillary forces, thus allowing the hydrocarbons to flow through the formation;

b) the vibrations which propagate inside the reservoir in the form of elastic waves modify the contact angle between the formation and the fluids, and reduce the coefficient of hydraulic friction. Thus, easier flow takes place towards the wells, where a drastic increase in the velocity, as well as a larger pressure drop, occurs;

c) the elastic waves generate an oscillatory force in the layers, and, due to the different densities of the fluids, these accelerate differently. Due to the different accelerations, the fluids "rub" each other and generate heat by friction, which in its turn reduces the

interfacial tension of the fluids.

In addition to these effects, the vibrations release the gas which was trapped, thus, which shall contributing to an expressive effect to increase oil pressure.

In addition, the oscillatory force creates an oscillatory sonic pressure which contributes to the oil flow.

To maintain, and at the same time to increase, the field pressure, heat is applied to the reservoir when the natural pressure has decreased. Heat is applied both in the form of frictional heat, caused by vibrations, and in the form of alternating current supplied to the wells. Due to the capacity of electrical current transmission, always present in the reservoir, the current circulates in the wells and will make the reservoir act if it were an electric furnace, so that a resistive heating is consequently obtained.

The heating will cause partial evaporation of water and of the lightest fraction of petroleum hydrocarbons.

The alternating current will make the ions in the fluids oscillate and thus create capillary waves in the surface of the fluids, thus reducing the interfacial tensions.

The total heat generated both by the electrical stimulation and by the vibrations will reduce the viscosity of the fluids (ie. will render them thinner).

Both the vibrator and the electricity supply menas are placed in petroleum producing wells and, thus, the oil which flows acts as a refrigerating medium, which allows the utilization of a large energy density.

These basic facts were verified by means of tests conducted on a laboratory scale and based on the principle previously described. The results of one of those tests are represented in Figure 2.

The graph shows, as a function of time, the oil recovered from the production wells. The production of each well, the total production, and the type of stimulation applied during the tests, were traced, as follows: V represents the vibrations only, E represents electricity only, and V + E represents vibrations together with electricity. After 80 hours the test was interrupted and later on restarted. Even so, the results were impressive.

The graph indicates that, with the process of the present invention, the recovery was 3.5 times greater than in the primary recovery. The results of the previous tests were nearly equal.

What is important to observe in this test is that a drastic increase in oil production occurred with the stimulation by means of the simultaneous application of electrical and vibrational energy. Oil production occurred earlier than would be expected for the thermal effect by means only of pressure increase and drastic changes in viscosity. This confirms the theory that the surface tension decreases with the oscillation of the ions in the fluids, which generates a fast increase in oil flow, together with acoustic stimulation, which accelerates the droplets.

It is necessary to explain better how the sound waves can affect petroleum production and what has been verified in our intensive laboratory research.

The movement mechanisms in a reservoir can be as follows:

1. Fluid and matrix expansion.
2. Water displacement.
3. Gas displacement.
4. Solution-gas displacement.

The process of this invention may be utilized together with all those mechanisms, but its results are best in the case of solution-gas displacement.

In case of gas dissolved in oil, the gas expands in the form of small droplets inside the oil as pressure decreases, or as the reservoir is heated when pressure is below saturation pressure.

The gas bubbles displace the oil, which flows inside the reservoir following the pressure gradient. The oil droplets are usually surrounded by water and very few solid particles exist on which the bubbles can grow. In this case an increase in the bubble point will occur in accordance with the increase in the boiling point, and the pressure in which the bubbles are formed will be substantially lower than for a given temperature. Therefore, it is necessary that the pressure be reduced for the bubbles to be able to start growing on the microbubbles which may be present in the liquid. It has been shown that the acoustic vibrations interact with the increase in the bubble point, so that boiling may more easily start.

In addition, the surface tensions at the interface between oil and gas shall prevent the oil from flowing inside the reservoir. Those surface tensions at the interface between oil and gas are relatively low and decrease as temperature increases. Therefore, a very large effect will be achieved with relatively weak vibrations.

Our laboratory tests showed that, from the rock matrix in which the flow stopped, it is possible to restart the flow with a vibration as weak as 0.04g. With this a recovery of up to 80% of the residual oil has already been achieved.

The explanation for that is that when the oil flow stops it is because a point of equilibrium has been reached, which can be altered by means of a weak acoustic stimulation.

As sound oscillations propagate in the radial direction of the well, and oil flow in the same direction, an optimum effect shall be achieved with the utilization of a minimum amount of energy.

In addition it is known that oil, and other fluids, flow more easily through a porous medium when said medium is affected by vibrations, a fact which is attributed to the reduction of hydraulic friction in the pores. This explains why a liquid, considered as Newtonian, acts as if it were a thixotropic fluid in small droplets. In the limiting area between the liquid which flows and the limits of the pores, the molecules shall become "aligned" with some molecules in the thickness, according to their higher or lower polarity.

If the liquid is subject to vibrations one reaches what is referred to as capillary waves in the fluid, and then the molecules will not have the time to establish polar links. The thixotropic layer becomes thinner and the oil will flow more easily. This phenomenon interacts with the oscillatory movement of the ions in the same surfaces, and will thus be superimposed on the capillary waves created by the vibrations.

The energy in the sound wave which is absorbed by the reservoir will be transformed into heat and will therefore increase the gas pressure as a consequence of the above mentioned partial evaporation, together with the electrical stimulation.

It is a great advantage that the heat be generated in the reservoir itself and that it does not have to be transported to the layers, by conduction, or by means of a heat-carrying medium, such as steam, hot water, or equivalent.

At the time of water breakthrough in the producing wells, it often happens that large quantities of oil are retained in the reservoir due to the action of the capillary forces. Oil recovery has already been achieved in these conditions by means of sonic stimulation, but it was necessary to utilize strong vibrations (5-10g).

The above mentioned US Patent 4,884,634, prevents a system to achieve stimulation in a petroleum

reservoir by the simultaneous utilization of electrical and sonic means. It shows the main utilization of 3-phase electricity conducted into the wells with one or more vibrators immersed in a conducting liquid, such as mercury, placed in the same wells. It has the advantage of making the conducting liquid oscillate as if it were a rope with several knots, so that the waves propagate into the reservoir as shells which expand and are superimposed on each other, creating a "hammering" effect inside the layers.

However, this US patent does not deal with the details concerning the application of such a principle when the wells are old and when the equipment installed in them is of standard type.

This means that the process of the present invention is an innovation in the utilization of conventional production facilities and tools, and that the surface electrical system avails itself of usual equipment, such as commercially available transformers.

When trying to utilize the above principle in a reservoir, the following problems must be taken into account:

1. energy dissipation in the geological formations;
2. energy conduction to the vibrators;
3. control of total energy consumption;
4. obtainment of electrical and acoustic connection with the well casing and of the well casing with the reservoir, so that the use of a conducting liquid may be dispensed with; and
5. availability of a vibrator which is simple and durable, and which does not suffer from the instability usual in the vibrators already known.

One object of the present invention is to solve the problems mentioned above, allowing the process to develop in a practical way and to be adaptable to

practically any type of reservoir.

Another object of the present invention is to conduct the energy to the geological formations at the bottom of the hole, with or without special electric cables, as well as to utilize the energy to make the vibrators work.

It is another object of the present invention to interconnect the vibrator to the regular production tubing, making the electrical connections operate with or without hydraulic pressure in the tubing.

Still another object of the invention is to allow the vibrator to be tuned at different frequencies and transmit the so-called "pink sound".

One embodiment of the present invention involves conducting the electrical current through an electric cable installed in the annulus between the production tubing and the casing. The electrical connection is achieved by means of connectors, on a separate connector assembly, and which are either installed on the vibrator or connected to the uncovered end of the electric cable.

An alternative embodiment consists of conducting the electrical current through the production tubing, centralized in the casing by means of special non-conducting centralizers. In this option the annulus may be filled with isolating oil to avoid any electrical connection with the casing.

A further alternative embodiment consists of conducting the electrical current through the isolated casing, isolating the production tubing with the centralizers.

As regards the vibrator it may receive energy from the main feeding source. This energy will feed initially the vibrators and then, through the connectors, energy will pass to the casing, penetrating as far as the petroleum formation, or vice versa.

The vibrators may also be fed from the main feeding source, draining the energy from the main source to the vibrator, at a chosen pulse. This means that the main feed usually by-passes the vibrator, but is conducted to it when it is activated. This can be controlled from the surface or from the bottom of the hole by a discharge device.

The electrical isolation which remains above the petroleum formation may be achieved by cutting the casing at a short distance above the petroleum formation and filling the cavity with some type of isolating material, for instance epoxy, isolating oil, or similar. If desired, a fibreglass coating may be utilized above the petroleum formation.

With the purpose of making it easier to understand the invention, reference is made to Figures 3 to 14.

Figure 3 shows a general arrangement of three wells equipped with their conventional elements, well-known to the experts, such as wellhead 16 and flow lines 17 to the oil tank. From a 3-phase power source, either a generator or a transmission line, and starting from transformers and control units 19 the feeding cables 18 extend towards the wells. A standard casing is aligned at the well bore, the production string 20 being centralized inside the casing by means of centralizers 22. At the end of the string is a packer 23, known to the expert. The casing is cut at a certain distance 25 above the producing layer 24 to form a cavity which can be filled with isolating epoxy or similar.

Below this point vibrators 26 remain suspended from the production string 21. The current which flows through the vibrators, or by-passes them, enters the part of the casing which penetrates the petroleum layers, by means of hydraulically driven connectors 27, or of a mechanical connector made of a supporting device at the

bottom of the hole.

Figure 4 presents a typical view of the electrical circuit at the bottom of the hole.

The above mentioned power source may feed alternatively the externally-isolated casing 28 or an electrical cable 29 provided with reinforcement 30.

When the current is conducted by means of the electrical cable, this cable remains in the annular gap 31, established between the production string 32 and the internal wall 33 of the casing, as shown in detail A of Figure 4.

When the current is conducted by means of the externally-isolated casing 28, an electrical connector 35, which works hydraulically, remains attached to the string 32 and makes the contact directly in the non-isolated interior space 36, of the casing 28, located above the isolation bridge 34.

The current which leaves the conducting casing 28 through the conduit 37, or through the electrical cable 29, flows through the vibrator 38 and enters the lower casing 39 by another connector 35, which also works hydraulically.

Figure 5 shows a well, ready for the process of the invention, provided with an isolated casing 28 as conducting element, and a vibrator 26 with hydraulically operating connectors 40, 41. In addition, the well bore is enlarged at the petroleum layers 24, as is well-known in the art, and the cavity 42 is either filled with salty concrete and drilled or with spheres in aluminium or another metal, or else with another highly electrically conductive material, such as a metallic or non-metallic conducting liquid, aiming always at increasing the area of the electrode and providing a good acoustic connection with the petroleum-bearing formation.

Figure 6 shows the same arrangement as Figure 5, except that the vibrator 43 oscillates vertically.

The main problem during the development of the process of the invention consists of designing and constructing vibrators which are reliable, inexpensive and durable, and which can be synchronized at the natural frequency of the petroleum-bearing formations, as defined on page 187 in "RANDOM VIBRATION IN PERSPECTIVE", by Wayne Tustin and Robert Mercado, of the Tustin Institute of Techology, Santa Barbara, California.

> "NATURAL FREQUENCY, f_n - the frequency of the free vibrations of a non-muffled system; also, the frequency of any type of the normal vibration modes. f_n decreases in case of muffling".

Due to the muffling (attenuating) properties which are always present in any reservoir, and which can be evaluated by the Formation Quality Factor, it may be verified, through the work presented by Yenturin A. Sh., Rakhumkulov R. Sh., Kharmanov N. F. (Bash NlPlneft't), Neftyanoie Khkozvaistvo, 1986, No. 12, December, that the effective natural frequency is in the range of from 0.5 to 5Hz, and that it can provide an acoustic pressure pulse of 2 to 20MPa, depending on the pressure prevailing in the reservoir.

However, we verify that this frequency can reach nearly 100Hz, and, as an example, we may mention a Brazilian petroleum field where the pressure is 16.7 bar (1.67Mpa). It has been verified in this case that the optimum average sound pressure was 304KPa which results in a pressure gradient of 108KPa and an acceleration of 5g in the casing. We have thus a vibrator with an average power of 100kW = 18kW/m^2. At 5Hz this may generate a maximum intensity peak of 362kW/m^2 and a sound pressure of nearly 5MPa.

The low frequency herein described generates acoustic waves of deep penetration. But, since it would be advantageous to have available much higher frequencies

close to the well area, to achieve the effect of emulsification and then to contribute to a lower hydraulic friction, this question is solved by making the vibrator transmit what is referred to as "pink sound", which means noise containing many frequencies, which is incidentally the case of most noises. For instance, recording the low-frequency noise of given musical instruments, such as drums, it can be verified that there is a number of different frequencies at the upper part of the low-frequency wave.

Since the effect of muffling in the reservoir will absorb the low frequencies immediately around the well, the object of the invention is automatically reached by transmitting low-frequency "pink sounds". No method known for stimulation with vibrations has already called attention to this point.

In petroleum well logging operations a series of vibrators is known which can transmit high powers at various frequencies. None of such equipment, however, has shown itself to be adequate to the purposes of the present invention, since they have not been designed for continuous utilization. In addition, they do not allow for the associated use of electrical stimulation, nor can they be fed from the main power source towards the wells.

Consequently, it was necessary to design special electromechanical vibrators to meet the requirements of the present invention. To reach this purpose it was verified that it would be necessary to convert electrical energy to magnetic energy, and this to kinetic energy in a body, and hence in a high-power acoustic pulse. Such electromechanical vibrators are shown in Figures 7 onwards, which will now be described as follows.

Figure 7 shows a vibrator which works vertically, and which includes a series of coils which, upon being energized, drive a magnetised (armature) tube

within the coils, which transmits the thus-generated kinetic energy to a hammer 44 which alters the direction of the movement in elastic waves. This is achieved by means of the following elements: the coils 45 are connected in series to a full-wave rectifier 46; the rectifier 46 is connected to the main supply conductor 47 which in the present case consists of the production tubing 32 and the lower part of the casing 39. Above the rectifier 46 is a general switch driven by a thyristor 48. This switch opens at a given frequency by means of a time circuit 49. As the switch 48 opens, the direct current flow towards the coil, and the magnetic fields then generated in the coils, pull the tubular armature 50 downwards. A sensing coil 51 at the end of the path closes the switch again, and a spring 52, or the pressure inside the reservoir, will pull the tubular armature 50 upwards again. The oil flows through the tubular armature and carries away the heat generated in the coils.

There now follows a detailed description of the hammer device 44 which receives the stroke of the tubular armature 50.

Figure 8 shows an alternative for the hammer device 44, which includes a bar 44 with V-shaped bodies 44A attached to the bar 44. At a certain distance below the V-shaped bodies 44A are moving bodies 44B, the upper part of which is V-shaped. The bodies 44A, 44B may have different shapes and thus create different wave patterns as the bar is pressed into the liquid. The waves will be generated as the fluids between the moving bodies 44B and the fixed body 44A are pressed radially outwards, since the high acceleration downwards of the bar causes the bodies to be pressed against each other at high speed. By placing the opposite sides of the bodies parallel to the bar 44, it is possible to make the casing bend axially as seen in detail A-A. The great advantage of this is that deformation of the casing requires much less force than

when steel is drawn, as it occurs with the utilization of a vibrator which sends force impulses in all directions at the same time. By allowing the sides of the bodies to follow a long helix, as seen in the drawing, it is possible to make the casing oscillate as a musical instrument string, thus transmitting pulses of superimposed waves into the layers.

On the other hand, the tubular armature may hit any construction which may change the direction of the vertical movement of nearly 90°.

Another hammer device is shown in Figure 9. The expansion element is in this case a flexible tube which consists of an axially corrugated steel tube. The downwardly pointing end of the expansion element is closed by a cover 35. At the other end the tube 54 is connected to a terminal part 55 where there is a piston 56. The piston 56 can be pushed by the tubular armature 50 shown in Figure 8, into the expansion tube 57, which is filled with a liquid. The piston 56 is returned by means of the spring 52 or by any other elastic means. The expansion tube may have any suitable cross-section, as seen in details A, B, C and D, and all of these will generate different wave patterns and allow the casing to bend axially as mentioned above.

Another vibrator utilizes the vector product between the electrical and magnetic flows, which results in a perpendicular force F, which is the base for all electrical motors, availing itself of the second electrical current used for the wells. This alternative is disclosed in accordance with Figure 10, where there is a core 57 built of rolled steel sheets, as in the armature of a motor. In the core is a coil made of isolated copper wire 58, both the core and the windings being protected by insulation 59. For the expansion element various options exist, of which four alternatives are shown.

In a first option for the expansion element,

the expansion element is a corrugated tube 60 made of stainless steel. The annular gap between the tube 60 and the insulation 59 is filled with a liquid of high electrical conductivity, for instance mercury. Instead of utilizing a corrugated pipe, we may replace it by a flexible hose 61 made of silicone rubber.

Another option for the expansion element is for the tube 62 to be divided into four elements 63. In the gap between adjacent poles 64 is an iron bar 65 attached to the tube 62. The various tubes 62 are maintained united by means of an elastic silicone hose 66.

Still another option is a corrugated tube 67 of special format.

The operation of the vibrator is as follows.

The current i from the conductor of the well passes first through the coil 68 and thus generates a magnetic flux B between the poles 63, 64. Thereafter the current passes through the expansion element (in the first two options constituted by the conducting liquid), and then into the petroleum-bearing formation. The circuit is arranged so that the force F may act against the casing and the producing formation. As the direction of the current and of the magnetic field changes, due to the alternating current frequency, the frequency of the vibrations will duplicate. That is to say if the current is at 50Hz frequency, the frequency of the vibrations will be 100Hz.

In some reservoirs this may be the optimum frequency, and therefore it will not be necessary to manoeuvre the force to the vibrator. But if it should not be advantageous to utilize a lower frequency, the force may be fed as described for Figure 7, or by transmitting a high-voltage pulse from the surface, which makes the current pass through the coil in the vibrator and hence into the producing formation. This force may be fed also from a charged capacitor, or from a coil as in the ignition system of a car.

Figure 11 shows another option for a vibrator.

The coupling scheme 69 shows the hydraulically operated connector 35 attached to the end of the production string 32 with its insulated packer 23 below the enlarged area 70. The vibrators can also be seen, in the form of a core 71 composed of iron sheets united by means of a bolt 72 and a nut 73. At each end of the core are two terminal parts 74 which press on the bundle of rolled iron sheets forming the core 71. Around the core is wound a coil 75 of copper wire which, upon being energized, generates a magnetic field with north and south poles at each side of the core, as seen in the section A-A of Figure 11. In order to protect them, the coil and the core are placed inside a non-magnetic tube 69 having the section shown. The spacing between the core/production tubing set 76 and the steel casing is nearly 1mm.

The operation of this vibrator is as follows: as the current passes through the coil 75 and then through the connector 35, and into the formation, an oscillating magnetic flow B is generated in the coil, which changes in direction in accordance with the alternation frequency of the current. Since the oscillating magnetic flux will attract the casing in the same direction, it will vibrate at twice the frequency of the power source, according to detail A-A, due to the electricity of the steel. This results in the same advantages pointed out in relation to the movement of the casing dealt with above, for the expansion element of the vertical vibrator shown in Figure 7.

For the case of large thicknesses of the producing formation, the core of Figure 11 may be twisted and it shall be thus possible to make the casing vibrate, transmitting wave trains from the casing, and to superimpose the knots.

Should it be required to utilize a frequency lower than the alternation frequency of the electric

current, this may be obtained in the same way as that described for the vibrator of Figure 7, which energizes the coil with high current pulses. It is also convenient to point out that all the shocks generated by the vertical vibrator automatically generate pink sounds. To achieve these pink sounds in the vibrators which transmit horizontal shock waves, and which vibrate at twice the frequency of the power source, a frequency modulator is used. In its simplest form this may be done with a tape recorder whose signal is amplified by a transformer. We may verify that it is thus possible to utilize special "music" for frequency modulation.

In the case of the vibrator which operates in accordance with the principle described in Figure 11, it may be advantageous to build it with a special expansion element which vibrates instead of the casing. This is achieved by installing the coil assembly set 72 inside an additional flexible tube which may be caused to vibrate. The cross-section of this expansion tube may be circular or elliptical.

Figure 12 shows still another vibrator. The coupling scheme 69 shows the hydraulically operated connector 35 attached to the end of the production string 32 with its insulated packer 23 below the enlarged area 70. Below the coupling 69 is a void space 77 intended for the switches which control the vibrator 78. The vibrator consists of a series of coils 79 attached to each other by means of spacers 80 and tube sections 81. In the central holes of the coils, for each pair of coils, there are two iron pistons 82, with their ends which face each other chamfered in parallel at a 45° angle. The coils are wound so that for each pair of adjacent pistons, the magnetic poles which face each other remain of opposite polarity. The plane end of each piston 82, which faces the piston of the other pair of coils, has the same magnetic pole as it does. A hole is drilled in the sections of pipe 81, in

which two small pistons 83 are placed in opposite direction, and the end turned to each other is cut in parallel at a 45° angle. The various coils with their pistons are placed in a steel tube 84 which is closed at the bottom by a plate 85.

The function of the vibrator is to transmit an electrical current into the coils, which will generate magnetic fields and the above mentioned magnetic polarities. The pistons 82 attract to each other and press the small pistons 83 radially outwards. The vertical movement of the pistons 82 and, therefore, the kinetic energy absorbed as they reach the pistons 83, will be transformed into acoustic energy as the steel tube 84 is bent. Without using an expansion pipe 84 the power would be transmitted from the radial pistons 83 as a burst.

Each end of the pistons 83 will transmit elastic waves of high power and low frequency. Even though the magnetic field increases slowly, the sudden impact on the ends of the piston 83 will make possible the generation of pulses of several kW.

These statements are supported by the following equations.

For calculation purposes, the magnetic flux density in the air gap between the poleshoes is assumed homogeneous. Also, the residual magnetic field in the ferrous material, the current induced by the frequency fluctuation in the magnetic field, and the magnetic losses in other parts of the circuit are assumed negligible.

The Ampère Law shows that:

$$\oint H\,dl = I$$

where: H = magnetic field strength

l = circuit length

I = electric current

The magnetic force may be expressed as:

$$F = \frac{dw}{dx} \quad \frac{1}{2} \quad \frac{B^2}{\mu} \quad . \quad A \qquad (1)$$

where: F = magnetic force

W = magnetic power

X = field displacement

B = magnetic flux density

A = transversal area of the magnetic circuit

μ = magnetic permeability

Then, the magnetic field is:

$$\oint H \, dl = I_{total}$$

$$\oint H_{Fe} \, dl + 2 \, H_{air} \, \delta = NI$$

where: δ = size of the air gap

N = number windings in the coil

Assuming $H_{Fe} \simeq 0$, we will have $2 \, H_{air} \, \delta = NI$ (2)

Thus:

$$H_{air} = \frac{1}{2} \quad \frac{NI}{\delta} \text{ and } B_{air} \frac{1}{2} \quad \frac{NI}{\delta} \mu_0 \quad (3)$$

Combining equation (3) into equation (1):

$$F = \frac{1}{2} \quad \frac{B^2}{\mu} \quad . \; A = \frac{\mu o}{8} \left(\frac{NI}{\delta} \right)^2 .A \quad (4)$$

This equation shows that the magnetic force increases parabolically, as an inverse function of the air gap size. This indicates that the force will dramatically grow until the instant of impact.

Considering, for project purposes based on Figure 12, the following values

$A = 0{,}02 \; m^2$; $N = 1000$; $I = 5$ Amperes ; $\delta_{max} = 0{,}01mm$; $m = 5kg$, the magnetic force corresponding to each position of the piston and the accumulated power at the end of piston travel, can be calculated. The results are shown in Table I.

δ_x [m]	$F=\frac{\mu o}{8}\frac{NI}{\delta}^{2} \cdot A$ [N]	$a = \frac{F}{m}$ [m/s^2]	$v=v_o+\sqrt{2as}$ veloc.at δ_x [m/s]	$E=\frac{1}{2} mv^2$ [kW]
0.0100	785	157	0.18	0.08
0.0090	970	194	0.38	0.36
0.0080	1300	260	0.61	0.93
0.0070	1600	320	0.86	1.85
0.0060	2180	436	1.16	3.36
0.0050	3140	628	1.51	5.70
0.0040	4900	980	1.95	9.50
0.0030	8700	1740	2.54	16.13
0.0020	19600	3920	3.43	29.41
0.0010	78500	15700	5.20	67.60
0.0005	314000	62800	8.75	191.18

At the impact point ($\delta = 0$), the power should be infinite. However, a realistic value can be estimated as 100 Joules and the time for dissipating this energy 0.001 second, Thus, the power per plunger will be:

$$W = \frac{100}{0.001} = 100 \text{ kW}$$

Each train of waves of the small pistons 83 will be superimposed on the others, since the waves will be superimposed on each other.

The arrangement of coil set 79 and pistons 82 shown in Figure 12 results in an axial movement of said piston. However, it can advantageous to turn the coil/piston assembly through 90° so as to obtain a radial movement of the piston.

Still another alternative for the vibrator is shown in Figure 13. The coupling scheme shows the hydraulically operated connector 35, attached to the end of the production string 32 with its insulated packer 23, below the enlarged area 70. Below the coupling 69 is a void space 77, intended for the electrical switches of the vibrator. The vibrator consists of a series of coils 87 wound around a core of iron sheets 88 so that each magnetic pole in the ends of the coils is identical. This means that the north pole of a coil is turned to the north pole of the north, and the south pole of that is turned to the south pole of the following coil. The cores of rolled iron 88 are formed so that each iron end of the coil is the same in each coil. The set of coils, in one of the possible arrangements, is placed in a square hollow tube 89 of elastic magnetic material, like a steel spring, with a space for the coils 87 and the rolled iron core 88. In another arrangement, the tube 90 is circular and of the same type of material, and therefore the ends of the rolled cores facing into the tube are circular. It must be understood that it is possible to utilize rolled tubes where the internal tube is made of an elastic magnetic material and the external tube is made, for instance, of stainless steel.

The operation of this vibrator is described as follows. When the electrical current passes through the coils 87 and then the connector 35 and into the producing formation, an oscillating magnetic flux B is generated at the coils, which changes in direction with the frequency of the current. Due to the fact that the magnetic poles in the coils face each other, a closed magnetic circuit will be obtained for each coil, as shown in Figure 12. Since the oscillating magnetic flux will attract the tubes, it will vibrate at twice the frequency of the main source. Since the attracting is stronger between the coils, the assembly will transmit a number of wave trains larger than

the length of the vibrator. Each wave pulse will have, in its vertical projection, the format shown in Figure 13, and in its horizontal projection, the format illustrated in details A and B of Figure 13. The advantages of this are the same as indicated for the movement of the tube, and therefore of the casing, as mentioned for the expansion element of the vertical vibrator of Figure 7. It must be pointed out that it is possible to attract the casing directly without using the expansion tubes 89 or the non-magnetic tubes as protectors of the coils.

To reach the low frequency, this may be achieved as for the vibrator of Figure 7 or as shown in the scheme of Figure 14.

The direction of the main current which is heating the producing formation, represented here as impedance Rj, may be changed by means of a thyristor adjusted at a frequency to pass through the vibrator and then activate the coils LVIBR.

With the use of rolled tubes, in which the external tube is non-magnetic, the magnetic tube serving as armature will reach the external tube as it returns, after the magnetic force ceases, and will then generate a sharp pulse as that described for the vibrator of Figure 12.

In addition, it has been verified that the interaction of the electrical and acoustic stimulation results in an effect much stronger than the utilization of either of those stimulations separately.

The distribution of heat and energy in the reservoir by the electricity and by the sonic waves may be calculated in the same way as the heat effectively released by friction. The friction caused by sonic stimulation is created by the oscillation of the fluid droplets but, due to the electricity, it is generated by the molecular movement. The total energy input is thus limited by the cooling capacity of the oil produced. The calculation for this is simple:

$$Q = M\,c\,(t_2 - t_1) \quad \text{(kJ/time unit)}$$

where: M = mass of petroleum for each time unit (kg/h)

c = specific heat of petroleum (kJ/kg°C)

t_2 = well temperature

t_1 = average reservoir temperature

It should be noted that any of those vibrators can be used for well- or any other logging and/or stimulation known in the art, such as coalescing, vibro-drilling, de-icing of soil, fracturing etc.

C L A I M S

1. A process for increasing the recovery of petroleum from petroleum reservoirs, wherein the producing formation is simultaneously subject to electrical and vibratory stimulation, in which the electrical current is supplied to the reservoir by means of an electric conductor installed in an annular gap between a production string and a well casing; wherein part of the energy is utilized to operate a vibrator attached to the end of the production string, the electrical connection being obtained by means of hydraulically driven connectors located at the vibrator and attached to the uncovered end of the electric cable; wherein said connectors conduct the electric current to the well casing which penetrates the producing formation at a point located above an isolation bridge; wherein part of the well casing is located above the producing formation and there is a cut at a certain height above said producing formation defining a cavity which is filled with an electrically insulating material.

2. A process according to claim 1, wherein the current is supplied to the reservoir by means of the production string which is centralized inside the casing by means of electrically insulating centralizers.

3. A process according to claim 1, wherein the current is supplied to the reservoir by means of an isolated casing.

4. A process according to any of the preceding claims, wherein the vibrator is of mechanical type which reciprocates vertically, energized by current impulses supplied to the reservoir as alternating current, as direct current pulses tapped from the main power source, or as pulses supplied from capacitors, transformers or magnetic coils, all energized from the main power source.

5. A process according to claim 4, wherein the energy of the vertical displacement may be oriented at

approximately 90°, and may be amplified, hitting the different expansion elements, such as a bar having attached thereto v-shaped moving bodies located in several manners so that, as the bar is displaced, each second body moves against the other and compresses the liquid between the bodies, generating pressure pulses capable of making the casing oscillate in several ways in accordance with the acoustic characteristics of the reservoir.

6. A process according to claim 4, wherein the vibrator may be oriented at nearly 90° and have its action amplified by displacement of a piston into a liquid contained in expansion tubes of different cross-sections, so that the various sound waves may make the casing oscillate in different ways in accordance with the acoustic characteristics of the reservoir.

7. A process according to claim 4, 5 or 6, wherein the energy of the vertical displacement of the vibrator may impinge on any expansion devices, which may alter and/or amplify the course of the original vertical displacement.

8. A process according to claim 1, 2 or 3, wherein the vibrator is of the electromechanical type which reciprocates horizontally, energized by current pulses originating from the alternating current fed to the reservoir itself, or by pulses of direct current tapped directly from the main power source, or by pulses supplied by capacitors, transformers or magnetic coils, all of them energised from the main power source.

9. A process according to claim 8, wherein the pulse of the vibrator is generated through the momentum resulting from the superimposition of electrical and magnetic fields; wherein the magnetic field is generated by a coil wound around a rolled core; and wherein the expansion elements which conduct the current are a corrugated tube in stainless steel and filled with a conducting liquid, or a hose made of silicone and filled with a conducting liquid, or a steel tube divided into current-conducting elements

united by a support means attached thereto.

10. A process according to claim 9, wherein said support means are a silicone hose or a corrugated steel tube.

11. A process according to claim 8, 9 or 10, wherein the pulse of the vibrator is activated by the attraction of a special expansion tube towards the steel casing, due to a magnetic field generated from a coil wound around a rolled core, so that said steel casing or the expansion tube acts as if it were the wave-transmitting element.

12. A process according to claim 8, 9 or 10 wherein the pulse of the vibrator is achieved by hammering pairs of bars located in the center of magnetic coils against radially oriented bodies by means of magnetic forces, so that the radially oriented bodies amplify the force in the hitting and orient it at 90° by hitting an expansion tube located externally to the coils, so that the expansion tube vibrates as if it were the wave transmitting element itself.

13. A process for increasing the recovery of petroleum from a petroleum reservoir, substantially as hereinbefore described with reference to the accompanying drawings.

14. Apparatus for increasing the recovery of petroleum from petroleum reservoirs, comprising a mechanical vibrator energized by current impulses supplied to the petroleum reservoir itself from the main power source; wherein said vibrator receives energy causing a displacement which can be oriented approximately at 90° and/or amplify the course of the original displacement by hitting different kinds of expansion devices which may make the casing oscillate in different ways in accordance with the acoustic characteristics of the reservoir.

15. Apparatus according to claim 12, wherein the vibrators can oscillate vertically and horizontally.

16. Apparatus for increasing the recovery of petroleum from petroleum reservoirs, constructed and

adapted to operate substantially as hereinbefore described with reference to, and as illustrated in, the accompanying drawings.

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Databases (see over)
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(ii) ON-LINE DATA BASE WPI

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Documents considered relevant following a search in respect of claims 1 TO 13

Category (see over)	Identity of document and relevant passages	Relevant to claim(s)
A	US 4884634 (ELLINGSEN)	1

Category	Identity of document and relevant passages	Relevant to claim(s)

Categories of documents

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